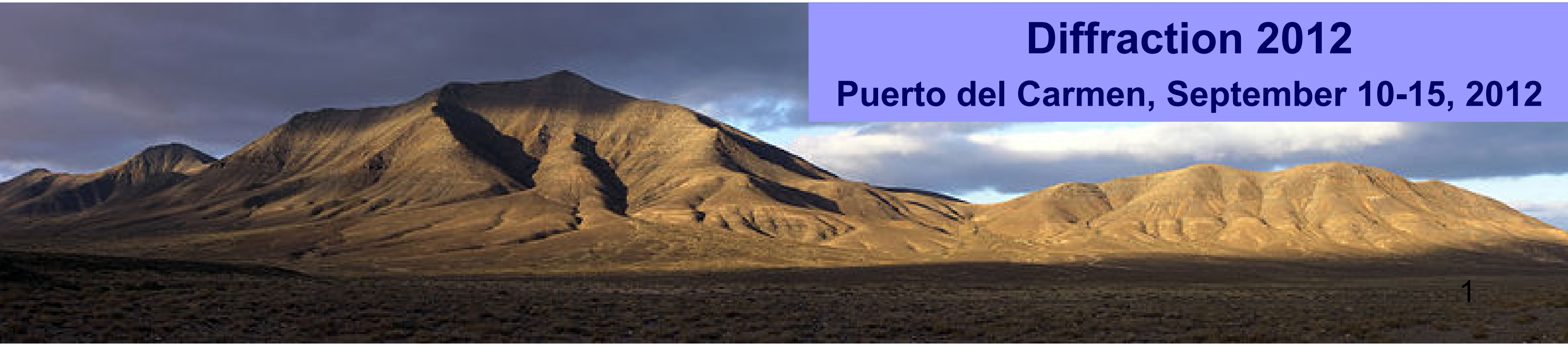
# Recent results from low-x and forward physics at HERA


**Lidia Goerlich**

Institute of Nuclear Physics PAN, Cracow

( on behalf of the H1 Collaboration )

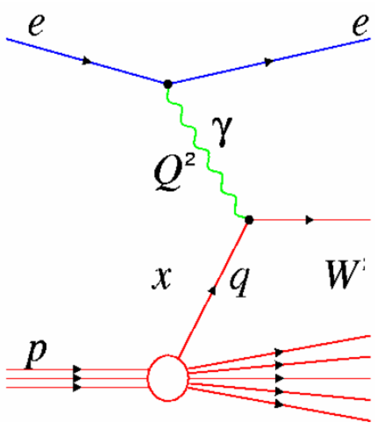

- **QCD tests with the hadronic final states**
- **Azimuthal correlation of forward jets in DIS**
- **Dijet production in diffractive DIS with a leading proton**
- **Summary**



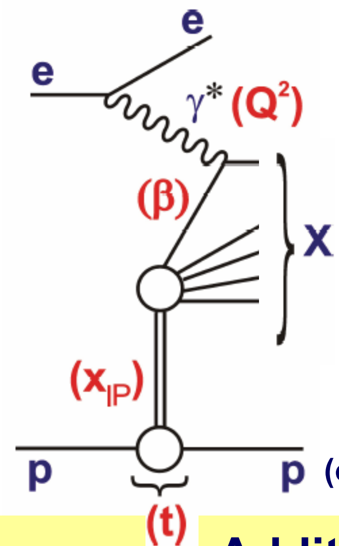
**Diffraction 2012**

**Puerto del Carmen, September 10-15, 2012**

## Deep inelastic ep scattering




## Diffractive DIS




(or low mass excitation)

~10% of DIS events at HERA have no activity in the forward direction ( Large Rapidity Gap )

→ exchange of a colourless object, called Pomeron (IP)

**Standard DIS variables :**

$Q^2$ virtuality of the exchanged boson

x in QPM fraction of proton momentum carried by struck quark

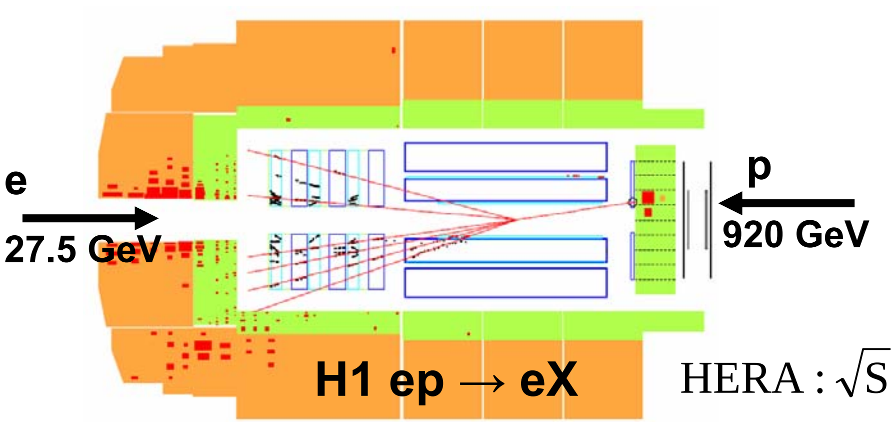
$y = Q^2 / xs$ inelasticity

**Additional variables for DDIS :**

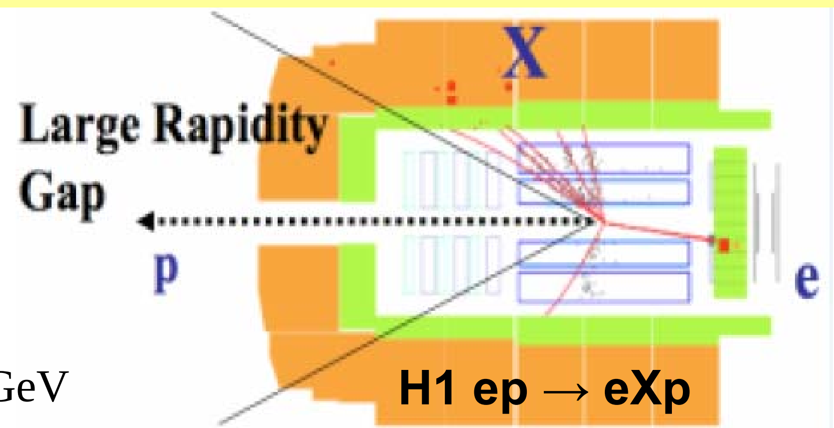
$x_{IP}$ p-momentum fraction carried by IP

β IP-momentum fraction carried by struck quark

t 4-momentum transfer at proton vertex

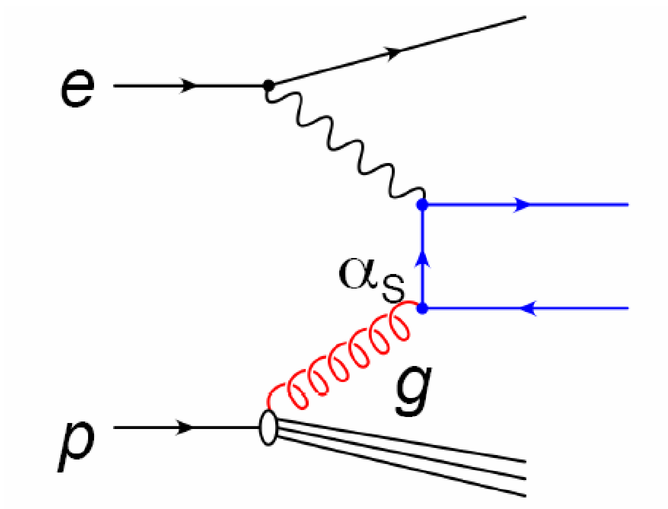


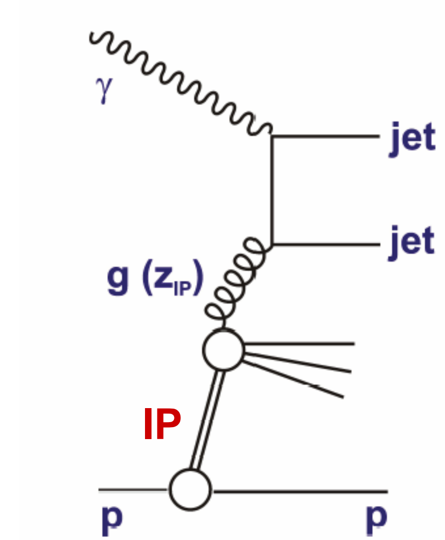

HERA : $\sqrt{S} \approx 300$ GeV



# Measurements of the hadronic final states

**Measurements of the HFS in DIS and diffractive DIS are complementary to inclusive studies**




- Information on the gluon density in the proton
- Determination of $\alpha_S$
- Search for effects of parton dynamics beyond the standard DGLAP approach

…

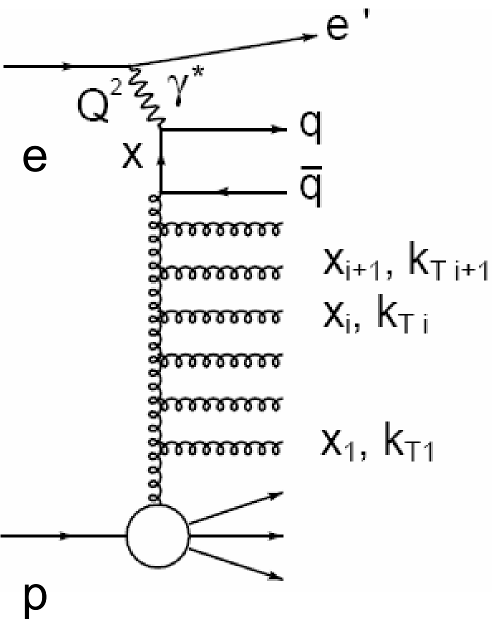
- Tests of QCD (inspired) models of diffraction
- Diffractive dijets - direct sensitivity to the gluon component of the Pomeron
- Search for physics beyond DGLAP parton evolution

…

# QCD dynamics at low Bjorken-x

**HERA : DIS at low Bjorken-x down to $10^{-5}$ $\rightarrow$ energy in $\gamma^*p$ cms is large ( $W_{\gamma^*p} \approx Q^2 / x$ )**

- **long gluon cascades exchanged between the proton and the photon**
- **pQCD – multiparton emissions described only with approximations :**

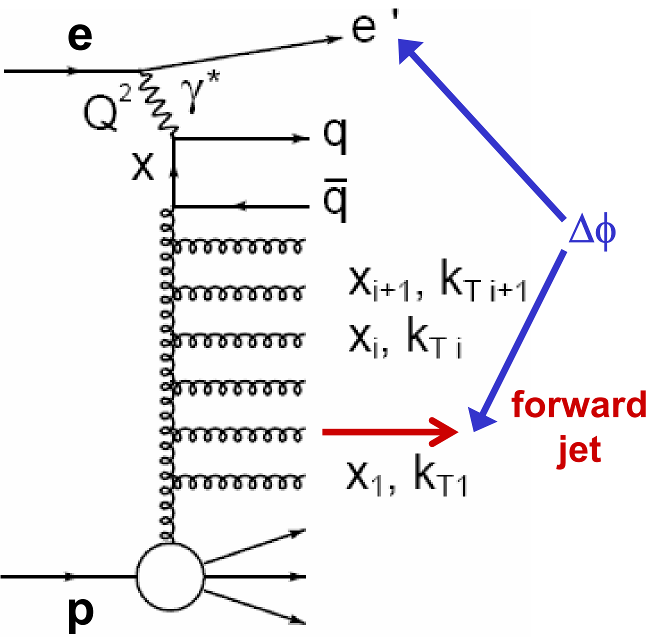



- **DGLAP evolution: resums terms ~ ( $\alpha_S \ln Q^2$ )$^n$**
  **Assumes strong ordering of parton $k_T$**
- **BFKL evolution: resums terms ~ ($\alpha_S \ln(1/x)$ )$^n$**
  **No ordering in $k_T$, strong ordering in $x_i$**
  **Transition from DGLAP to BFKL scheme expected at low x**
- **CCFM evolution: emitted partons are ordered in angles**
  **reproduces DGLAP at large x and BFKL at $x \rightarrow 0$**

**Search at HERA for effects of parton dynamics beyond the standard DGLAP approach**

- **Strong rise of the proton structure function $F_2(x, Q^2)$ with decreasing x**
  **– well described by NLO DGLAP over a large range of $Q^2$**
  **$F_2$ measurement too inclusive to discriminate between different QCD evolution schemes**
- **Look at hadronic final states – reflecting kinematics, structure of gluon emissions**

# Forward jets in DIS




## Mueller – Navelet jets in DIS (1990) :

**BFKL – more hard partons emitted close to the proton**

**Study high transverse momentum and high energy jets produced close to the proton ( forward region in LAB )**

**Suppress standard DGLAP evolution in $Q^2$ :**

$$p^2_{T,fwdjet} \approx Q^2$$

**Enhance BFKL evolution in x :**

$$x_{fwdjet} = E_{fwdjet} / E_p >> x_{Bjorken}$$

## Data selection

**~14000 forward jet events**

**H1 experiment, HERA data (2000) with 38.2 $pb^{-1}$**

$0.1 < y < 0.75, < Q^2 < 85\ GeV^2, 0.0001 < x < 0.004$

**Jets reconstructed in the Breit frame and boosted to LAB, all cuts in LAB**

$p_{T,\,fwdjet} > 6\ GeV, 1.73 < \eta_{fwdjet} < 2.79$

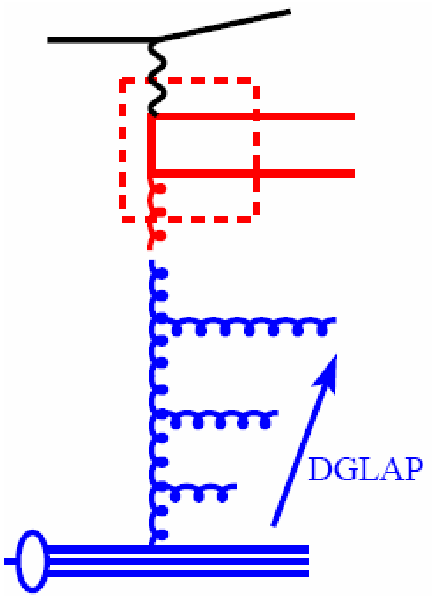
$x_{fwdjet} = E_{fwdjet} / E_p > 0.035, 0.5 < p_{T,fwdjet}^2 / Q^2 < 6.0$

**Measurement of the azimuthal angle difference $\Delta\phi$ between the scattered positron and the forward jet as a function of the rapidity distance Y between them.**

# Low x phenomenology : Monte Carlo models with different QCD dynamics

## RAPGAP - DGLAP

LO QCD matrix elements
+ HO modelled by leading log parton showers

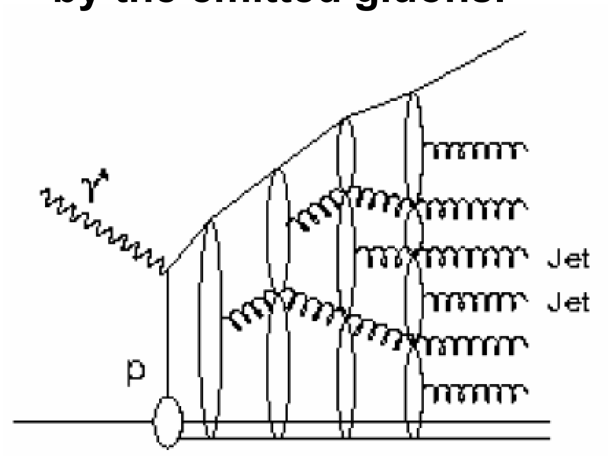



Single DGLAP ladder with strong ordering in $k_T$

## ARIADNE Colour Dipole Model

CDM: QCD radiation from the colour dipole formed by the struck quark and the proton remnant.

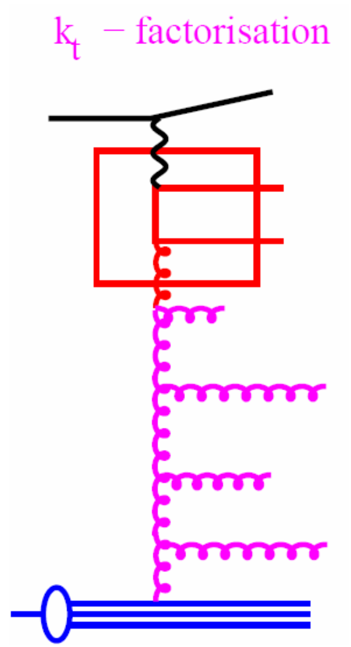
Chain of independently radiating dipoles formed by the emitted gluons.




BFKL- like Monte Carlo : random walk in $k_T$

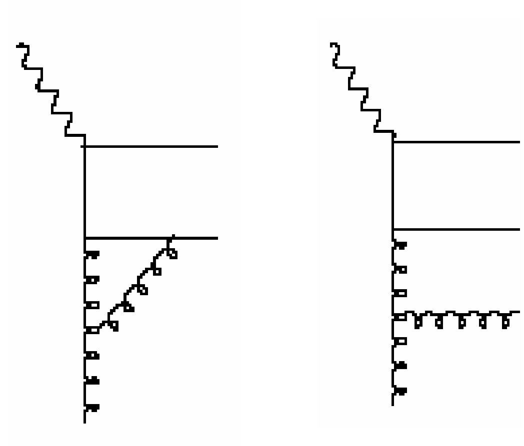
## CASCADE - CCFM

Off-shell QCD ME
+ parton emissions based on the CCFM equation




Angular ordering of parton emissions

## Forward jet cross sections – comparison with the predictions of pQCD at NLO ($\alpha_s^2$) accuracy

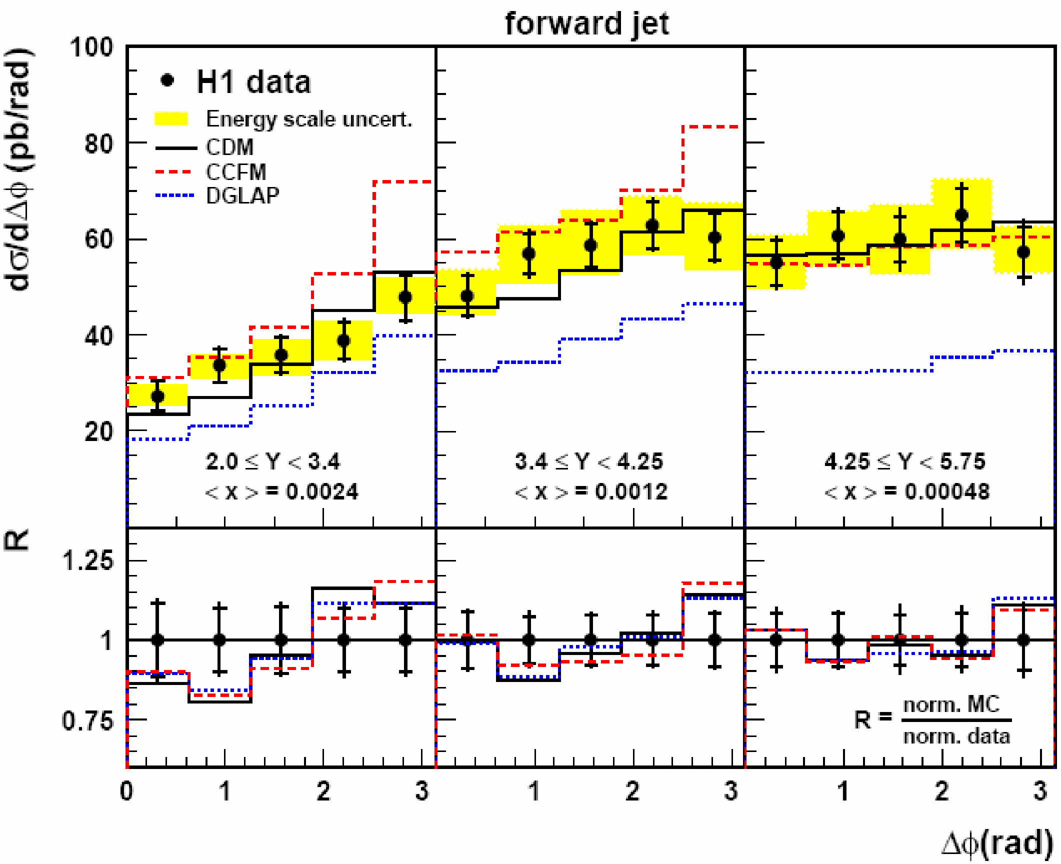


- **Forward jet analysis – reconstruction of jets in the Breit frame → at least dijet topology**

**NLOJET ++ program ( Nagy & Trocsanyi, 2001 ) :**
**dijet production at parton level in DIS at NLO ($\alpha_s^2$)**

- **PDF : CTEQ6.6, $\alpha_s(M_Z)$ = 0.118**
- **parton level cross sections corrected for hadronistaion effects using the RAPGAP model**

## At higher Y correspondig to lower x the forward jet is more decorrelated from the scattered positron




Eur. Phys. J. C72 (2012) 1910

**Cross sections best described by BFKL-like model CDM**

- **DGLAP predictions below the data**
- **CCFM (set A0) as good description as CDM at large Y**

**The shape of Δϕ distributions well described by all MC models**

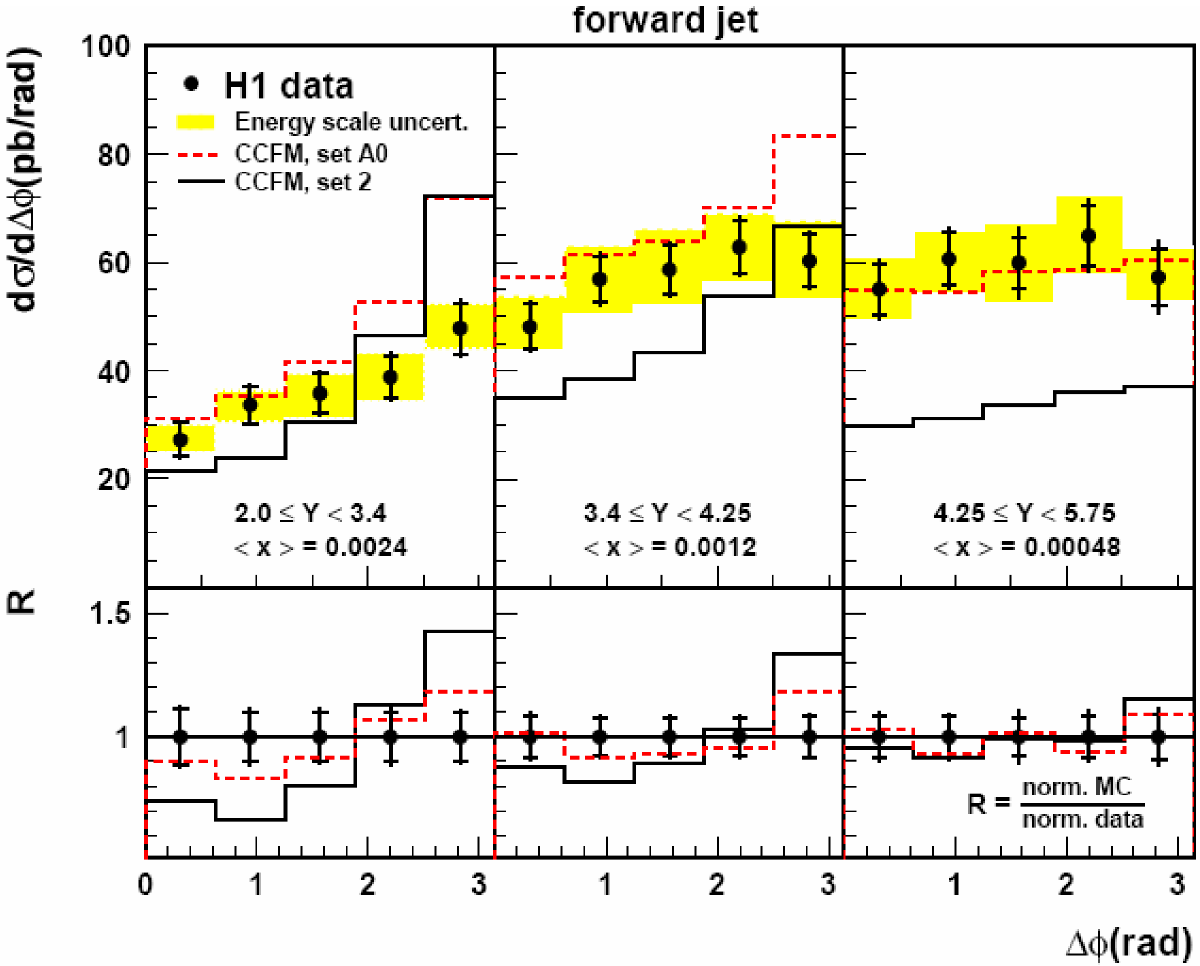
$Y = \ln(x_{fwdjet} / x)$ rapidity distance between the most forward jet and the scattered positron

$$R = \left(\frac{1}{\sigma^{\mathrm{MC}}}\frac{d\sigma^{\mathrm{MC}}}{d\Delta\phi}\right) \Big/ \left(\frac{1}{\sigma^{\mathrm{data}}}\frac{d\sigma^{\mathrm{data}}}{d\Delta\phi}\right)$$

# Forward jet azimuthal correlations

**Different splitting functions used in unintegrated gluon density function ( uPDF):**

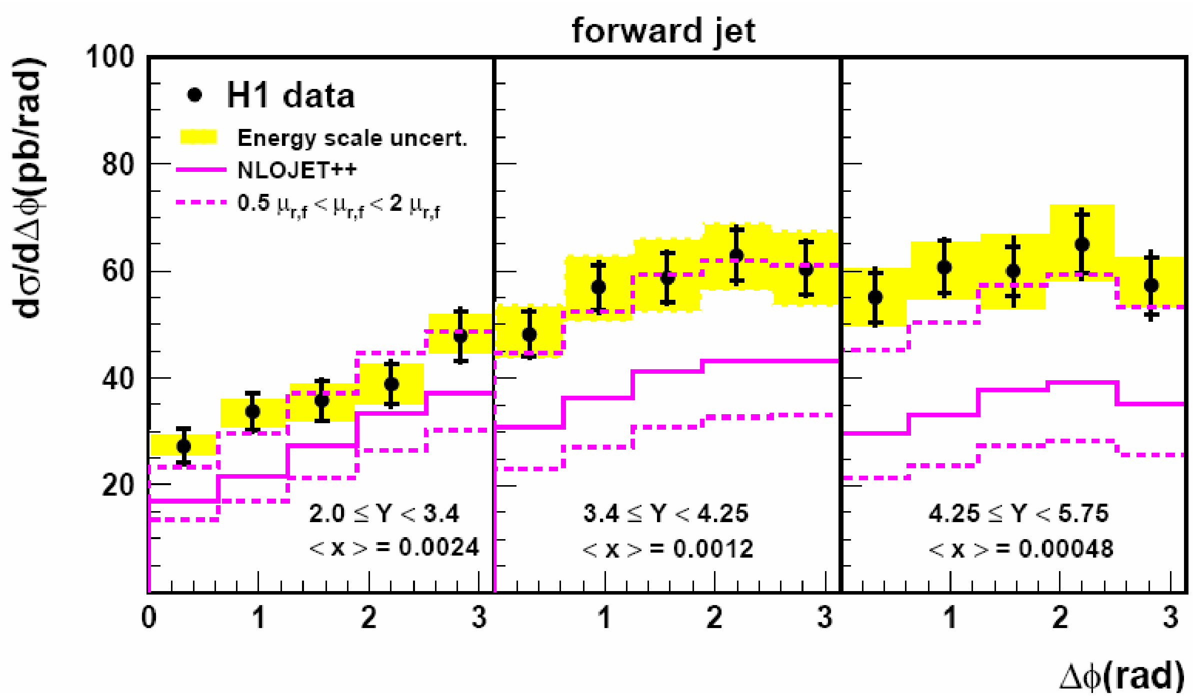
**set A0 – only singular terms of the gluon splitting function**
**set 2 – includes also non-singular terms**




- **Cross sections**
  **strongly depend on uPDF**
- **Shape of Δφ distributions**
  - **at low Y shows sensitivity to uPDF**
  - **well described by the set A0**

**Predictions of the CCFM model depend on the choice of uPDF**

## Comparison to NLO ($O(\alpha_s^2)$) predictions




**NLO predictions**

- shape of $\Delta\phi$ distributions described, but central value too low
- large scale uncertainty ( of up to 50% ) indicates importance of higher orders

**NLOJET++**

**PDF : CTEQ6.6, $\alpha_S(M_Z)=0.118$**

**renormalisation and factorisation scales :**

$$\mu_r^2 = \mu_f^2 = (p^2_{T,\,fwdjet} + Q^2) / 2$$

**theoretical uncertainty : factor 2 or ½ applied to $\mu_r$ and $\mu_f$ scales simultaneously**

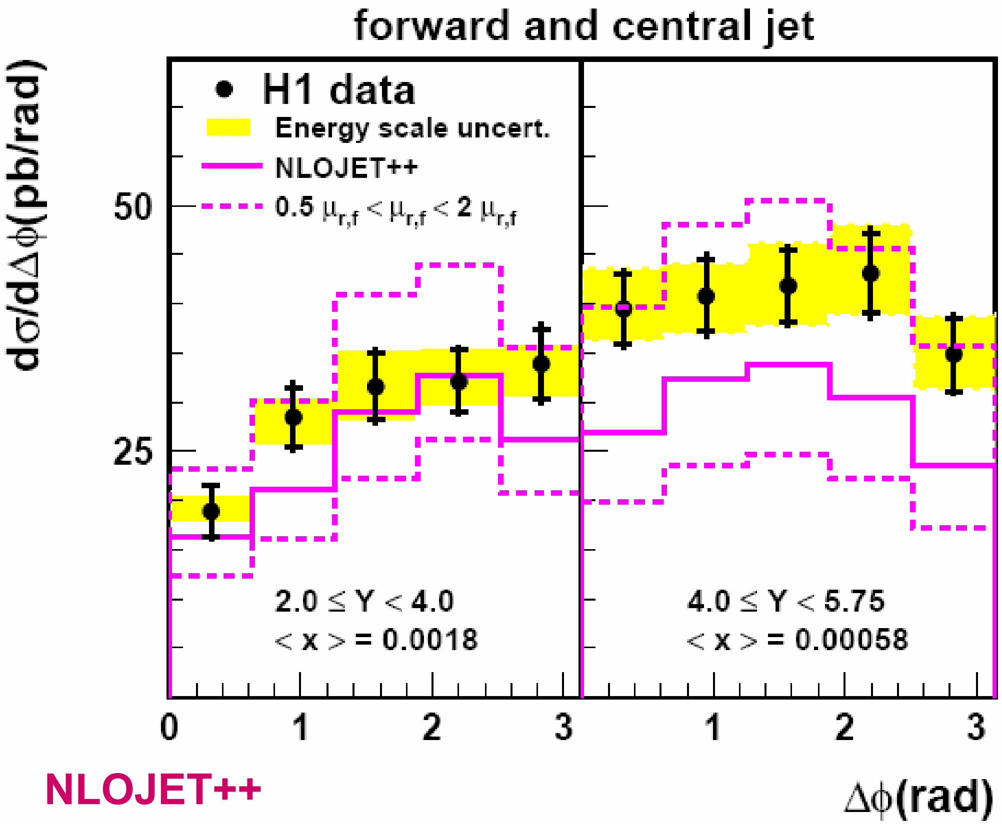
# Forward and central jet cross sections $d\sigma / d\Delta\phi$

- Subsample of events with forward jet + additional central jet

  $p_{T,cenjet} > 4$ GeV, $-1 < \eta_{cenjet} < 1$

  $\Delta\eta = \eta_{fwdjet} - \eta_{cenjet} > 2$ ( enhance radiation between the forward and central jet )

- $\Delta\phi$ still between the forward jet and the scattered positron




**NLO ($O(\alpha_s^2)$) predictions**

- at low Y reasonable description of the data
- at high Y, central value to small but still within theory uncertainty
- large scale uncertainty ( of up to 40% ) indicates importance of higher order contributions

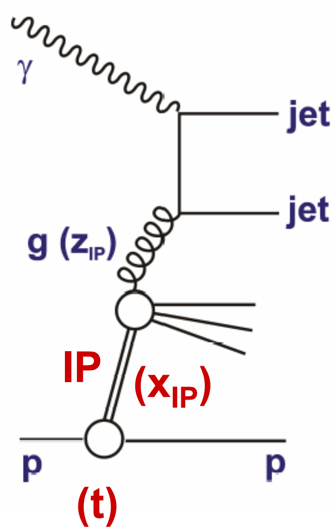
**NLOJET++**

PDF : CTEQ6.6, $\alpha_S(M_Z)=0.118$

$\mu_r^2 = \mu_f^2 = (\langle p_T\rangle^2 + Q^2) / 2$

$\langle p_T\rangle = 0.5\,(p_{T,\,fwdjet} + p_{T,\,cenjet})$

# Dijets in diffractive DIS with a leading proton




**$e\,p \rightarrow e\,jj\,X'\,p$**

**at least 2 jets + outgoing proton**
**measured in**
**the H1 Forward Proton Spectrometer**
**( no background from proton dissociation )**


**FPS @ H1**

- **2 horizontal Roman Pot stations at 61m and 80 m**
- **Scintillating fibres with PMTs + trigger tiles**
- **Acceptance :**

  $x_{IP} = 1 - E_{p'}/E_p$ up to 0.1

  $0.1\ \mathrm{GeV}^2 < |t| < 0.7\ \mathrm{GeV}^2$

**QCD hard scattering collinear factorisation at fixed $x_{IP}$ and t ( proved by Collins 1998) :**

$$d\sigma^{ep\rightarrow eXp}(\beta,Q^2,x_{IP},t) = \Sigma f_i^D(\beta,Q^2,x_{IP},t) \otimes d\sigma^{ei}(\beta,Q^2)$$

**$f_i^D$ – diffractive PDFs (DPDFs), DGLAP evolution in $Q^2$**

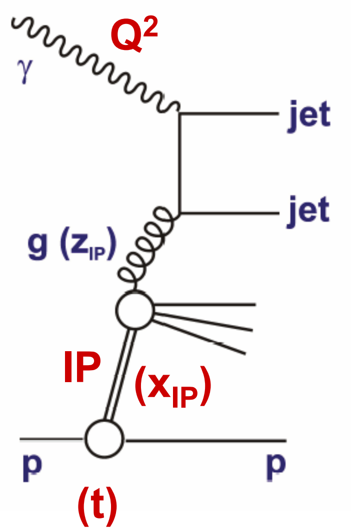
**Proton vertex factorisation: separate ($x_{IP}$, t) from ($\beta$, $Q^2$) dependences**

$$f_i^D(\beta,Q^2,x_{IP},t) = f_{IP/p}(x_{IP},t)\ \cdot\ f_i^{IP}(\beta,Q^2)$$

**No QCD basis,**
**consistent with experimental data**

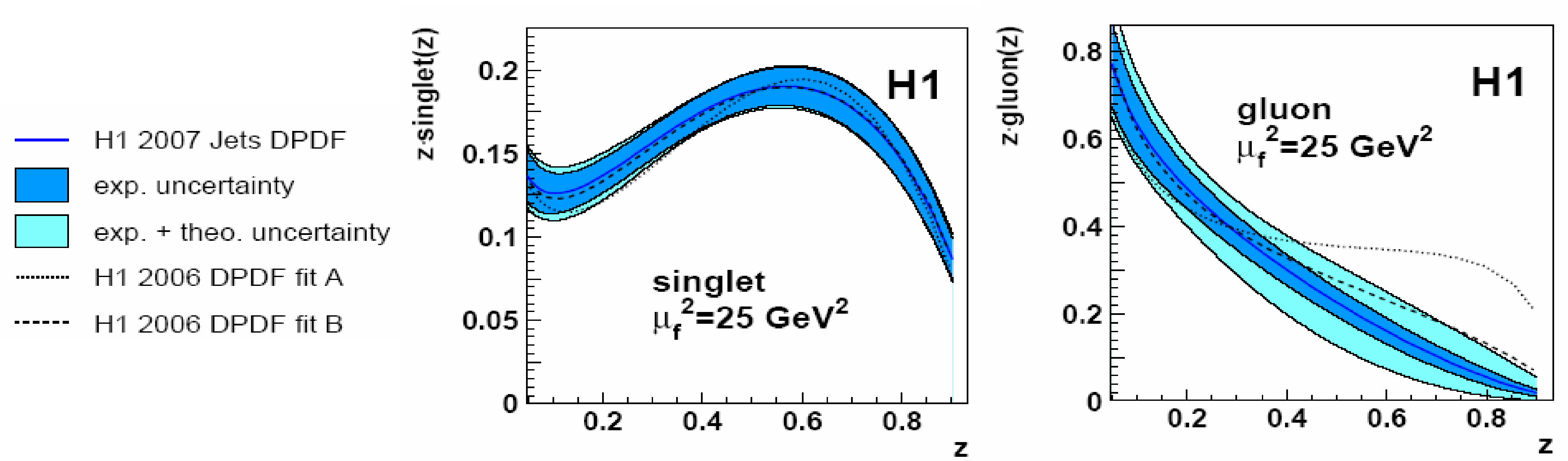
| Pomeron flux (Regge form) | Pomeron structure function |
|---|---|

# Diffractive PDFs

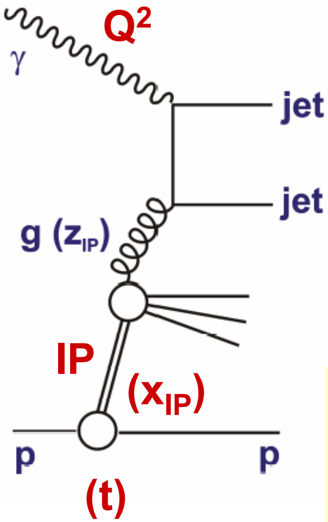



$z_{IP}$= momentum fraction parton / IP

- Diffractive PDFs extracted from
  - measurements of inclusive DDIS → H1 2006 DPDF Fit B (diffractive gluon density weakly constrained at high $z_{IP}$)
  - combined fit to diffractive inclusive and dijet cross sections → H1 2007 Jets DPDF (diffractive dijets constrain g($z_{IP}$) at high $z_{IP}$)
- The photon virtuality $Q^2$ and the high transverse momentum of jets provide a hard scale for pQCD calculations (program NLOJET++ modified for diffraction)



# Diffractive final states



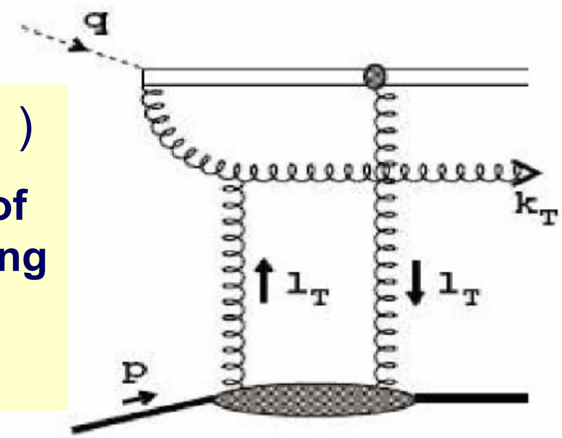

**Resolved Pomeron model** ( Ingelman & Schlein )
**based on QCD and proton vertex factorisation.**

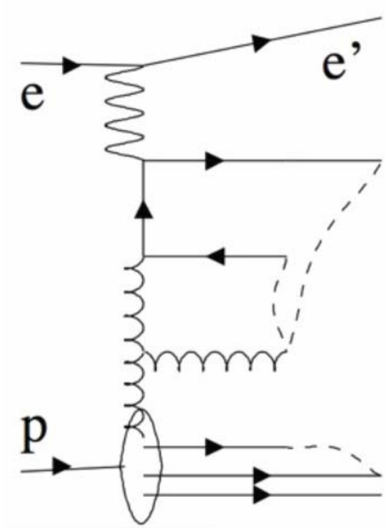
**( RAPGAP generator, IP + Reggeon trajectories, DPDF H1 2006 Fit B )**

**2 Gluon Pomeron model** ( J. Bartels et al. )

**Interaction of IP modeled as colourless pair of gluons with q$\bar{q}$ or q$\bar{q}$g configurations emerging from the photon.**

**( RAPGAP, unintegrated PDF – set A0 )**




**Soft Colour Interaction ( SCI )**
( Edin, Ingelman & Rathsman )

**Non-diffractive DIS with subsequent colour rearrangement between the partons in the final state.**

**Suppression of long strings ( SCI + GAL )**

**( LEPTO generator, PDF CTEQ6L )**

# H1 FPS – 2 central jets in diffractive DIS

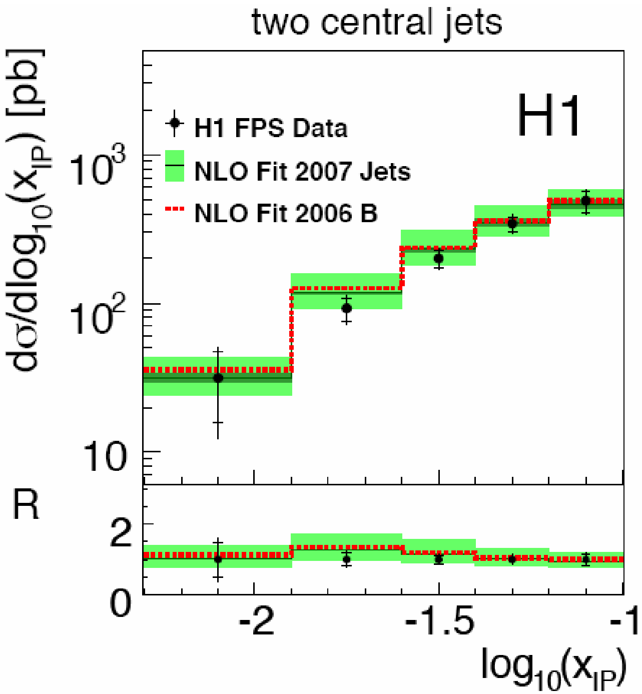
**Eur. Phys. J. C72 (2012) 1970**

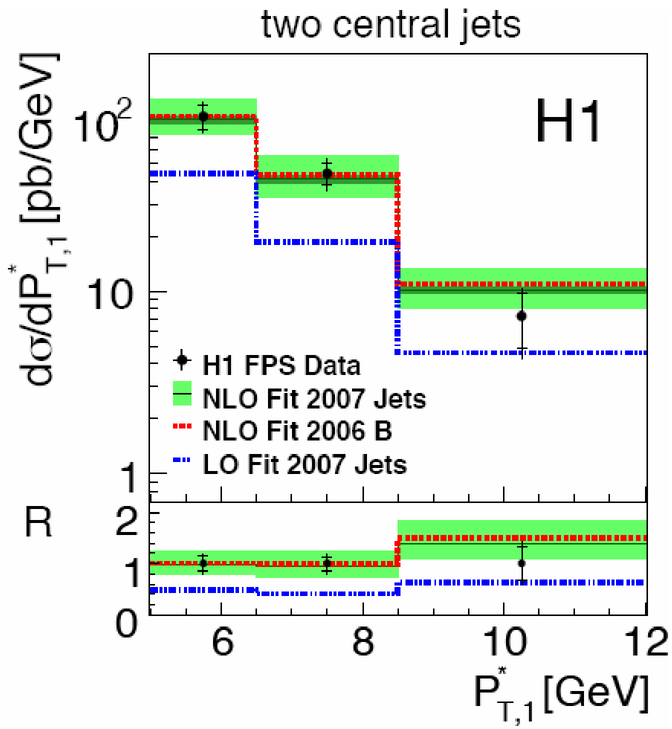
**HERA data (2005-2007) 156.6 $pb^{-1}$**

**$4 < Q^2 < 110\ GeV^2$, $0.05 < y < 0.7$, $x_{IP} < 0.1$, $|t| < 1\ GeV^2$**

**$p_{T,1}^* > 5$ GeV, $p_{T,2}^* > 4$ GeV, $-1 < \eta_{1,2} < 2.5$**

transverse momenta of jets in hcms



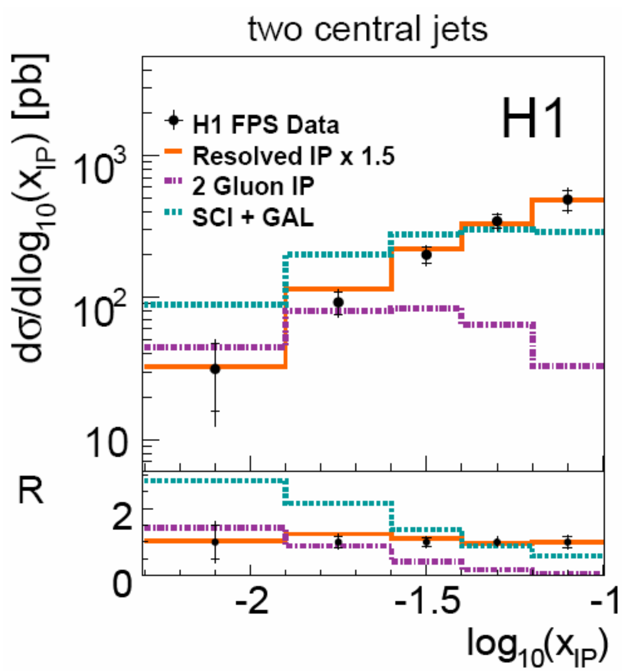



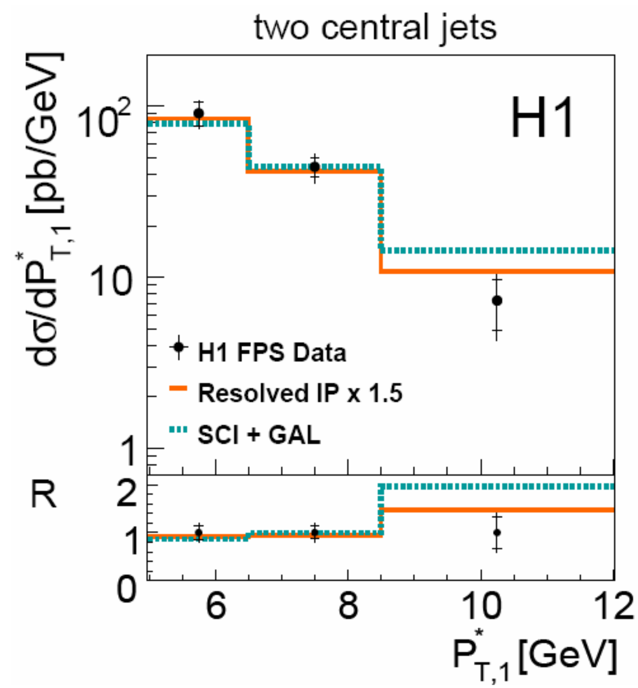

$$R = \frac{\text{prediction}}{\text{data}}$$

**NLO QCD predictions based on the DGLAP approach with DPDF sets H1 2006 Fit B and H1 2007 Jets describe the dijet cross sections within errors.**

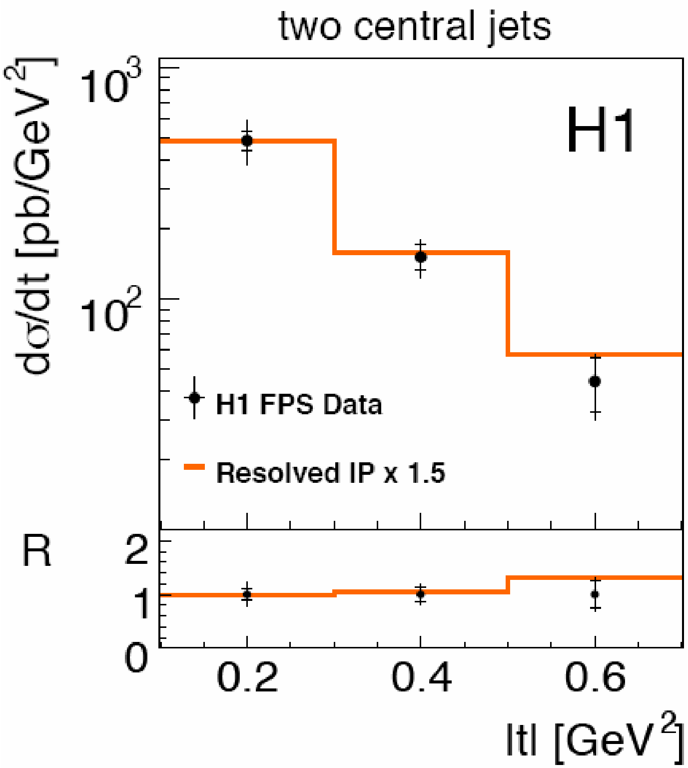
# Diffractive dijets – comparison with MC models

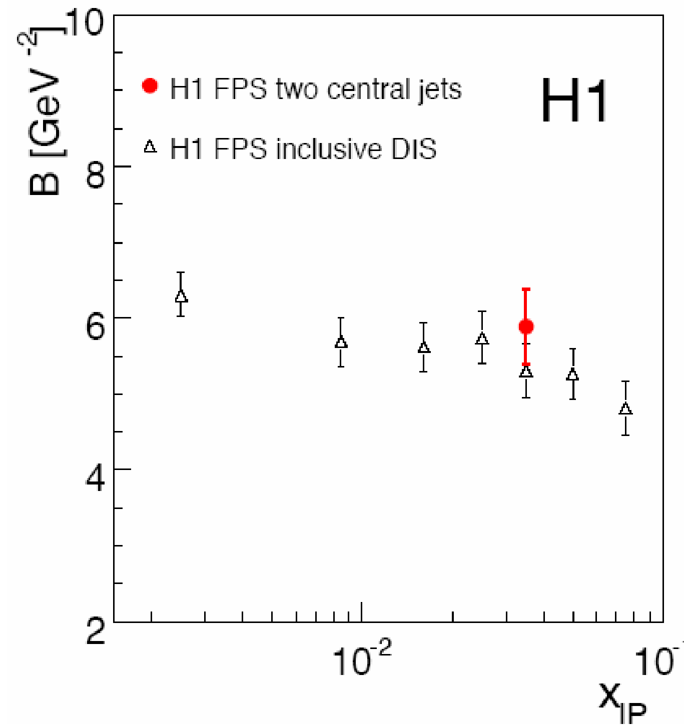
## MC models based on leading order matrix elements and parton showers




- Resolved IP model describes the shapes but underestimate the dijet cross section ( factor 1.5 ).
- SCI + GAL and 2 Gluon IP models fail to describe the shape of the distributions of the diffractive variables.
- SCI + GAL describes reasonably well the cross section as a function of the jet variables.




**Regge motivated fit exp(Bt)**

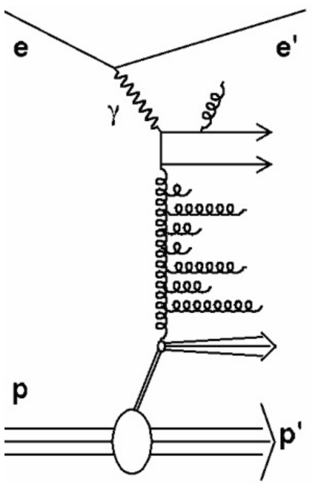
**→ $B = 5.89 \pm 0.50$ GeV$^{-2}$**

**t slope consistent with the value measured in inclusive diffractive DIS with a leading proton in the final state**

**Confirmation of the proton vertex factorisation hypothesis for diffractive dijet production**

# Diffractive forward jets

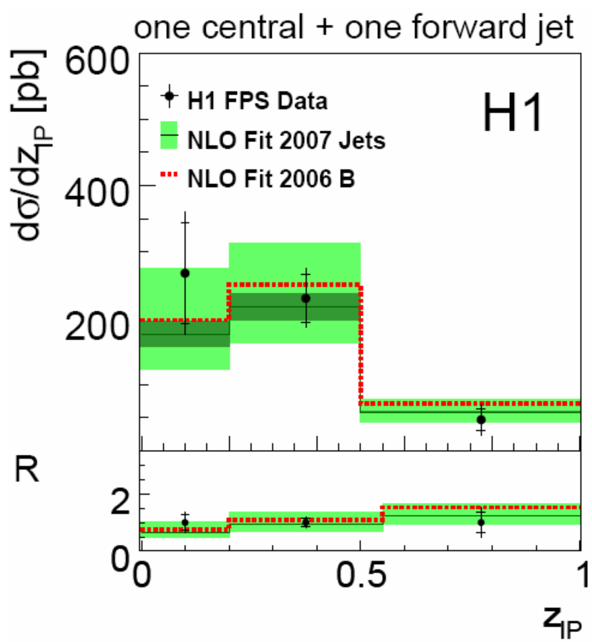
**search for physics beyond DGLAP**

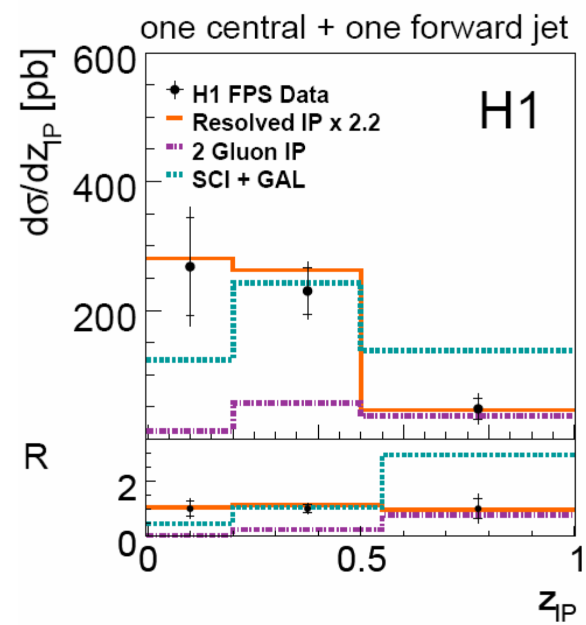


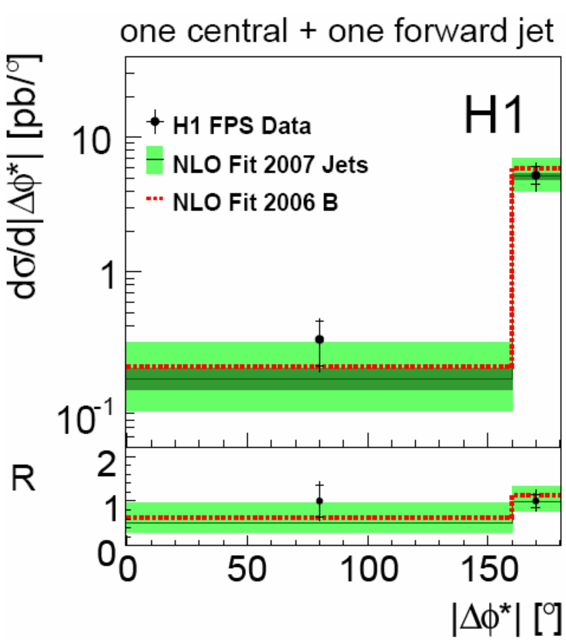

**one central + one forward jet**

**$4 < Q^2 < 110\ GeV^2$, $0.05 < y < 0.7$, $x_{IP} < 0.1$, $|t| < 1\ GeV^2$**

**$p_{T,c}^*, p_{T,f}^* > 3.5$ GeV, $M_{jj} > 12$ GeV, $-1 < \eta_c < 2.5$, $1 < \eta_f < 2.8$, $\eta_f > \eta_c$**




**No sign for deviations from DGLAP.**

**The shapes of measured distributions well described only by the Resolved IP model. ( too low in normalisation )**

# Summary

## Azimuthal correlation of forward jets in DIS

- Cross sections as a function of $\Delta\phi$ and rapidity separation between the forward jet and the scattered positron are best described by the BFKL – like model CDM
- The shape of $\Delta\phi$ distributions is well described by LO MC models with different QCD evolution schemes
- NLO DGLAP predictions are in general below the data, but still in agreement with the large theoretical uncertainties

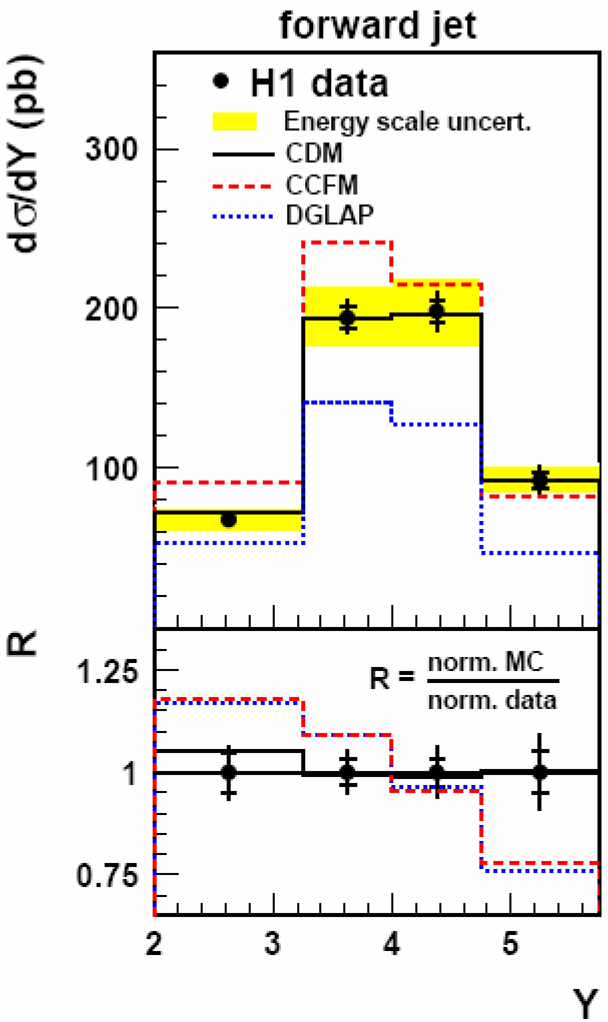
## Diffractive dijet measurement with a leading proton in the H1 FPS

- NLO DGLAP predictions using DPDFs describe the data within errors
- No deviation from DGLAP in the accessible phase space
- Confirmation of the proton vertex factorisation hypothesis
- LO MC models do not describe the data satisfactorily

**The data are in general more precise than NLO QCD predictions $\rightarrow$ challenge for QCD**

**backup**

# Forward jet cross section $d\sigma$ / dY



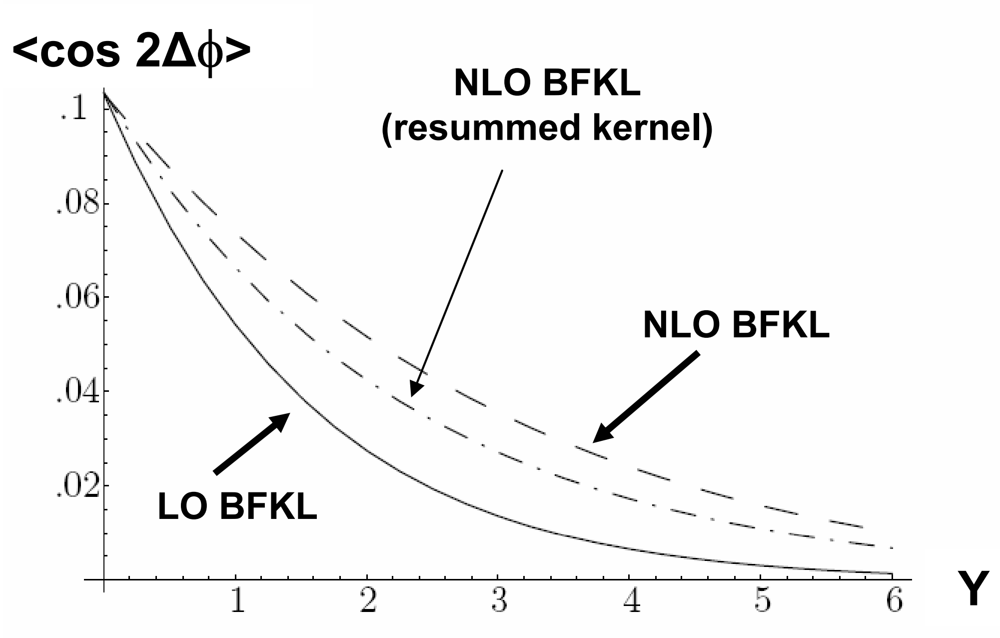

- BFKL–like model CDM describes the data best
- DGLAP too low, especially at large Y
- CCFM predictions to high at low x, but describe the data at large Y

**Y = ln($x_{jet}$ / x) rapidity separation between the most forward jet and the scattered positron**

# Forward jet production at NLO BFKL

S. Vera and F. Schwennsen, Phys. Rev. D77 (2008) 014001

**BFKL kernel at NLO accuracy**, jet vertex & photon impact factor using LO approximation




**Results**
**for forward jets with ZEUS cuts**

$20 < Q^2 < 100 \text{ GeV}^2$
$0.05 < y < 0.7$
$4 \cdot 10^{-4} < x_{Bj} < 5 \cdot 10^{-3}$
$0.5 < p_t^2 / Q^2 < 2.0$

$\Delta\phi = \phi_{el} - \phi_{fwdjet}$

$Y = \ln( x_{jet} / x_{BJ} )$ – evolution length in BFKL formalism

- The forward jet is more decorrelated from the scattered lepton for larger rapidity difference Y ( center of mass energy)
- The azimuthal angle correlations increase when HO corrections are included for a fixed value of Y

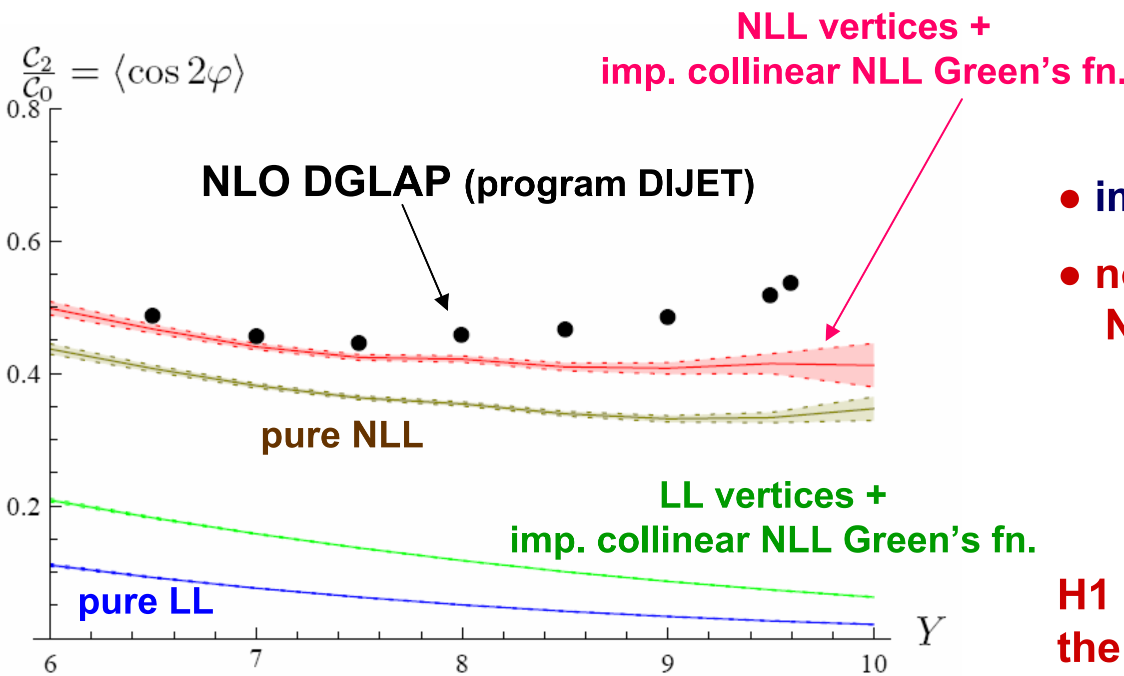
# Mueller- Navelet jets at LHC – complete NLL BFKL calculations

**Colferai, Schwennsen, Szymanowski & Wallon,**
**JHEP 12(2010)026**

**next-to-leading corrections to the Green's function and to the Mueller-Navelet vertices**

**LHC $\sqrt{S}$ = 14 TeV, $p_{T,jet1}$ = 35 GeV, $p_{T,jet2}$ = 50 GeV**

**Azimuthal correlation $\langle\cos 2\phi\rangle = \langle\cos(2 \cdot (\phi_{jet1} - \phi_{jet2} - \pi))\rangle$**

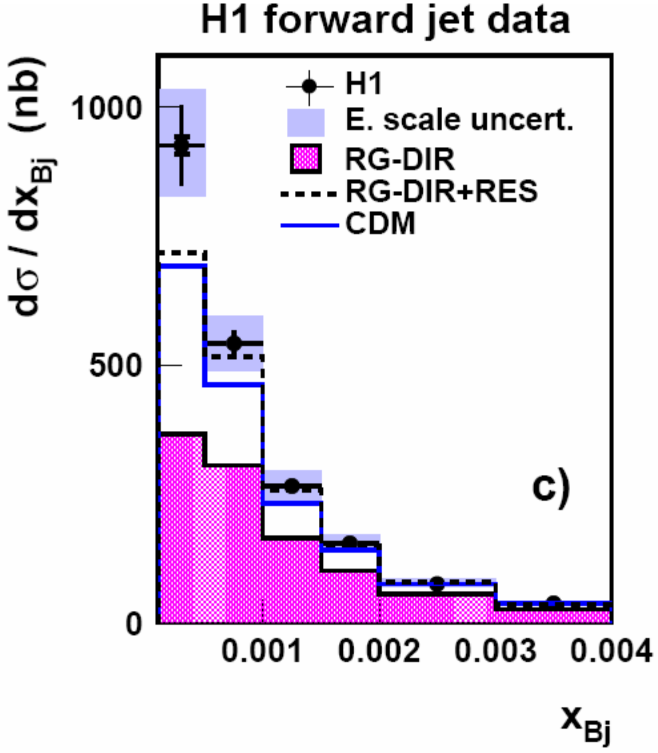



- **importance of NLL vertex corrections**
- **no significant difference between NLL BFKL and NLO DGLAP**

**H1 measurements →**
**the electron-forward jet decorrelation in DIS does not discriminate between different evolution schemes**

# Forward jet cross section dσ/dx

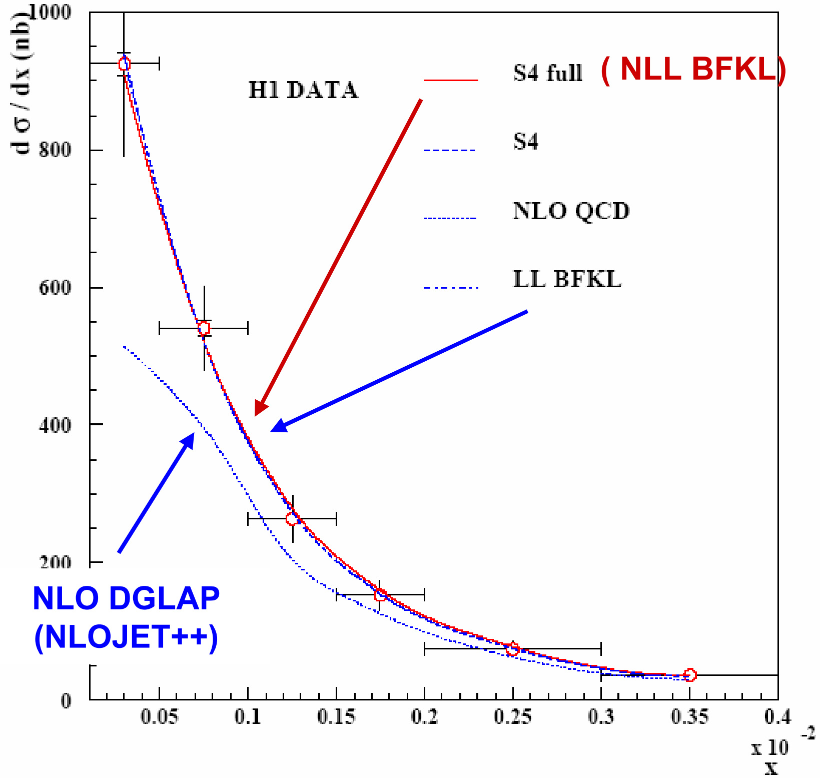
H1 data : Eur. Phys. J. C46 (2006)27




LO DGLAP (RG-DIR) below the data

CDM model and DGLAP resolved photon model (RG-DIR+RES) closest to the data, however the data are still below predictions at low x

BFKL calulations
Kepka, Royon, Marquet & Peschanski
Phys. Lett. B665 (2007) 236




NLO DGLAP below the data at low x

Difference between LL-BFKL and NLL-BFKL ( NLL BFKL kernel + free normalisation parameter ) is very small